

Carbon-enhanced metal-poor stars in different environments

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The origin of carbon-enhanced metal-poor (CEMP) stars and their possible connections with the chemical elements produced by the first stellar generations is still highly debated. We briefly review observations of CEMP stars in different environments (Galactic stellar halo, ultra-faint and classical dwarf galaxies) and interpret their properties using cosmological chemical-evolution models for the formation of the Local Group. We discuss the implications of current observations for the properties of the first stars, clarify why the fraction of carbon-enhanced to carbon-normal stars varies in dwarf galaxies with different luminosity, and discuss the origin of the first CEMP(-no) star found in the Sculptor dwarf galaxy.

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1 Background

In the Local Group, spectroscopic studies of ancient individual stars, provide us with the unique opportunity to uncover the chemical enrichment of the interstellar medium when the Universe was less than 1 Gyr old. Thus, the fossil imprint of extinguished first stars can be found in these old stellar populations.

For more than a decade, the chemical signature of primordial pair instability supernovae (SN) with masses $M_* = (140 - 260)M_\odot$ (Heger & Woosley 2002) have been looked for among the most metal-poor stars at $[\text{Fe}/\text{H}] < -3$, *in vain* (e.g. Cayrel et al. 2004). Still, state-of-the-art numerical simulations continue to predict that the first stars were likely very massive, $M_* = (10 - 1000)M_\odot$ (e.g. Hirano et al. 2014). Cosmological chemical evolution models for the Milky Way formation provide an explanation for such a tension between numerical findings and observations. “Second-generation” stars formed in environments polluted by pair instability SN *only*, are predicted to be extremely rare with respect to the overall Galactic halo population, and to have $[\text{Fe}/\text{H}] > -3$ if formed in small self-enriching galaxies (Salvadori et al. 2007; Karlsson et al. 2008). The recent detection of a *rare* halo star at $[\text{Fe}/\text{H}] \approx -2.5$, likely showing the chemical signature of pair instability supernovae (Aoki et al. 2014), might be the first indication that this is the case. Thus, to catch these elusive relics we need to increase current stellar samples. Where we can find, instead, the chemical signature of less massive and less energetic first stars? During the last few years an increasing number of carbon-

enhanced metal-poor (CEMP) stars, with $[\text{C}/\text{Fe}] > 0.7$ and $[\text{Fe}/\text{H}] < -2$, have been found in the Galactic stellar halo and in nearby dwarf galaxies. The most metal-poor among them, at $[\text{Fe}/\text{H}] < -3$, do not typically show enhancement in slow (or rapid) neutron capture elements produced by Asymptotic Giant Branch stars. Furthermore, they are not associated to binary systems, suggesting that their C-excess is likely representative of their environment of formation (Norris et al. 2010). These “CEMP-no” stars become more frequent as we move towards lower $[\text{Fe}/\text{H}]$, and their C-excess gradually increases (Fig. 1). CEMP-no stars at $[\text{Fe}/\text{H}] < -5$ show very peculiar chemical abundance patterns, which are consistent with birth environments polluted by $M_* = (10 - 40)M_\odot$ *primordial* faint SN that developed mixing and fallback (e.g. Iwamoto et al. 2005). A relatively good agreement with data is also obtained by models of *primordial* (or low-metallicity) “spinstars”, $M_* = (40 - 120)M_\odot$, that experience mixing and mass loss because of their high rotational velocity (e.g. Meynet et al. 2006). In conclusion, available observations support the idea of a link between CEMP-no stars and moderately massive first stars.

2 Observations and open issues

In Fig. 1 we show a collection of Carbon measurements in metal-poor stars dwelling in the oldest component of the Local Group: the Galactic stellar halo, ultra-faint dwarf galaxies, and the dwarf spheroidal galaxy Sculptor. According to hierarchical structure formation models, dwarf galaxies are expected to be the building blocks of stellar haloes (e.g. Helmi et al. 2008). Thus we are comparing

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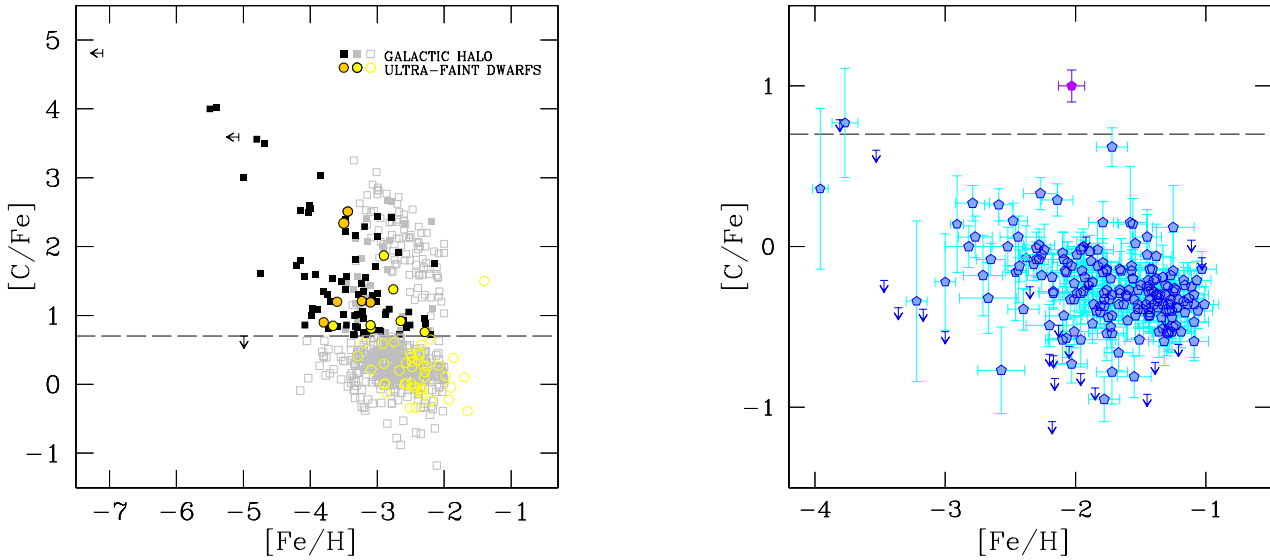


Fig. 1: Compilation of stars with measured $[C/Fe]$ and $[Fe/H]$ - see Fig. 1 of Salvadori et al. (2015) for references. *Left*: stars in the Galactic halo (*squares*) and ultra-faint dwarfs (*circles*). CEMP-no stars are shown with dark filled symbols (*black, orange*), light filled symbols show CEMP stars with no available measurements of slow (rapid) neutron capture elements, and open symbols all the remaining stars. *Right*: C and Fe measurements for stars in the Sculptor dwarf galaxy.

systems that likely experienced similar early star-formation histories. In Fig. 1 (left) we can first note that in the stellar halo C-enhanced and C-normal stars already co-exist at $[Fe/H] \approx -4.75$. A key question is then: what physical mechanism determines the formation of these different classes of stars? Are all CEMP-no stars second-generation objects?

We can also note that many CEMP-no stars have been found in ultra-faint dwarf galaxies, the faintest and most metal-poor satellites of the Milky Way, which have total luminosities $L < 10^5 L_\odot$. In these systems, the $[C/Fe]$ vs $[Fe/H]$ measurements follow the same trend observed in the Galactic halo, but the fraction of CEMP-no stars at $[Fe/H] < -3$ with respect to the total is even *higher* (Salvadori et al. 2015). Deep color-magnitude diagrams of ultra-faint dwarfs show that these galaxies are dominated by > 12 Gyr old stars (Brown et al. 2014), confirming that they might be the living fossils of the first galaxies, which formed prior the end of reionization and hosted the first stars (Bovill & Ricotti 2009; Salvadori & Ferrara 2009).

In the more luminous “classical” dwarf spheroidal galaxy Sculptor ($L \approx 10^{6.3} L_\odot$) instead, CEMP-no stars are much more rare than in the Galactic halo and in ultra-faint dwarfs (Fig. 1, right). In spite of very accurate and intense searches, no CEMP stars have been (yet) found at the lowest $[Fe/H]$ (see Skúladóttir et al. 2015). This result is quite surprising since Sculptor is also dominated by an old stellar population, and thus first stars are expected to be formed in this galaxy. If CEMP-no stars trace the early chemical enrichment by the first stars, why they are not observed in Sculptor? The puzzle became even more intricate after the discovery of first CEMP-no star in Sculptor (Skúladóttir et al.

2015). In fact, this star has an *unusually high* $[Fe/H] \approx -2$ (Fig. 1, right) although its chemical abundance pattern is consistent with an environment of formation also enriched by primordial faint SN (Skúladóttir et al. 2015). This observation poses several questions: does the fraction of CEMP-no stars depend on galaxy luminosity? Are CEMP-no stars at lower $[Fe/H]$ absent or hidden in Sculptor?

3 How do we interpret current observations?

To interpret these observations in terms of primordial cosmic star-formation and early galaxy evolution, we can use cosmological models for the build-up of the Local Group. Such a statistical tools, which catch the essential physics of early galaxy formation, follow the star-formation and chemical evolution of the Milky Way (Salvadori et al. 2007; de Bennassuti et al. 2014) and nearby dwarf galaxies (Salvadori & Ferrara 2009; Salvadori et al. 2015) along their possible merger histories by resolving star-formation in $10^{6.5} M_\odot$ mini-haloes (Salvadori & Ferrara 2009). The minimum halo mass to form stars is assumed to increase with cosmic time to account for the gradual effect of reionization (Salvadori et al. 2014). First stars with a variable mass distribution are assumed to form when the amount of dust and metals in the star-forming gas is lower than the critical value to allow gas fragmentation, $Z_{cr} < 10^{-4} Z_\odot$ (de Bennassuti et al. 2014). Otherwise, “normal” stars form according to a Larson initial mass function (IMF). Stars with different masses contribute to the chemical enrichment in their proper time scales, and SN explosions are assumed to eject

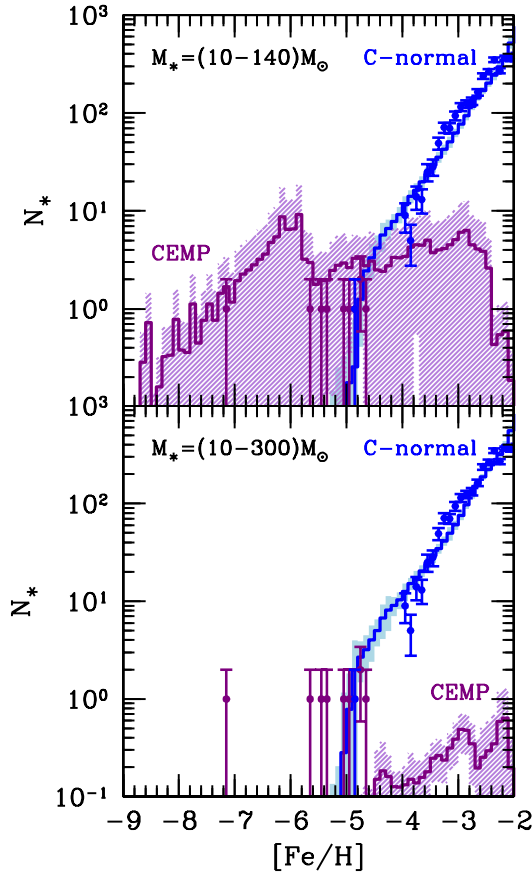


Fig. 2: The observed (*points*) and simulated (*histograms*) MDFs for Galactic halo stars obtained by assuming different mass ranges for the first stars (see labels). We show C-enhanced (*violet*) and C-normal stars (*blue*). Shaded regions are $\pm 1\sigma$ dispersion among 50 Milky Way merger histories.

metals and gas into the surrounding Milky Way environment, where the heavy elements gets instantaneously mixed (see Salvadori et al. 2014 for the inhomogeneous metal enrichment treatment). Both the efficiency of star-formation and the SN winds are fixed to reproduce the global properties of the Milky Way and they are assumed to be the *same* for all star-forming haloes. The only exceptions are mini-haloes, in which the star-formation efficiency is supposed to be reduced to account for ineffective cooling by molecular hydrogen (Salvadori & Ferrara 2009; Salvadori et al. 2015). For the details we remind the reader to the original papers.

Let’s first focus on Galactic halo stars. In Fig. 2 we compare the observed Metallicity Distribution Function (MDF) with model results obtained by assuming that first stars form according to a Larson IMF with different mass ranges: $M_* = (10 - 140)M_\odot$ (top) and $M_* = (10 - 1000)M_\odot$ (bottom). We can immediately see that the low-Fe tail of the MDF, which is populated by CEMP-no stars, is extremely sensitive to the assumed mass range of the first stars (de

Bennassuti et al. 2014). Our models show that a good match to the observations requires $M_* = (10 - 140)M_\odot$ (Fig. 2 top). This means that the early metal-enrichment should be dominated by primordial *faint* SN, which have masses $M_* \approx (10 - 40)M_\odot$ and produce large amounts of C and very small of Fe (e.g. Iwamoto et al. 2005). When the contribution from energetic pair instability SN is also accounted for (Fig 2, bottom), the chemical signature of faint SN is completely washed out and CEMP-no stars at $[\text{Fe}/\text{H}] < -4.5$ are not predicted to exist. According to our findings CEMP-no stars at $[\text{Fe}/\text{H}] < -5$ are truly second-generation objects, which have been enriched by primordial faint SN *only*. As we move towards higher $[\text{Fe}/\text{H}]$, CEMP-no stars form in environments polluted by both primordial faint SN and normal type II SN, which start to dominate the chemical enrichment at very high redshifts (Salvadori et al. 2014). Normal SN type II are the main pollutants of the inter-stellar medium of formation of C-normal stars, which are predicted to exist already at $[\text{Fe}/\text{H}] \approx -4.75$ (Fig. 2; de Bennassuti et al. 2014; Salvadori et al. 2015). In conclusion, the existence of CEMP-no stars at $[\text{Fe}/\text{H}] < -4$ provide key information on the mass range of the first stars, suggesting that faint primordial SN, with $M_* = (10 - 40)M_\odot$, must have dominated the early phases of chemical evolution.

Thus, to investigate the incidence of CEMP-no stars in dwarf galaxies with different luminosities, we can simply assume that the first stars have all masses $M_* = 25M_\odot$ and evolve as faint SN (Salvadori et al. 2015). With this working-hypothesis we find that, at $[\text{Fe}/\text{H}] < -3$, the average fraction of CEMP-no stars with respect to the total follows almost the same trend in all dwarf galaxies (see Fig. 3 of Salvadori et al. 2015). This “universal” shape is a consequence of the underlying hierarchical Λ CDM model for structure formation, according to which all galaxies built-up through merging of progenitor mini-haloes (e.g. Salvadori et al. 2010), where $[\text{Fe}/\text{H}] < -3$ stars predominantly form. In spite of that, we find that the probability to observe a CEMP-no star in a given $[\text{Fe}/\text{H}]$ range strongly depends on the galaxy luminosity and it is one order of magnitude higher in ultra-faint dwarfs than in the Sculptor dwarf galaxies (Salvadori et al. 2015). This is due to the dramatic change, with increasing luminosity, of the MDF of dwarf galaxies as shown in Fig. 3. We can see that, on average, the MDFs of ultra-faint dwarfs cover a broader $[\text{Fe}/\text{H}]$ range than Sculptor-like dwarfs. Furthermore, they are flatter, and thus contain more stars at $[\text{Fe}/\text{H}] < -3$, where CEMP-no mostly reside. Such a shape is a consequence of the low star-formation rate of ultra-faint dwarfs, which are predicted to be associated to low-mass mini-haloes (Salvadori & Ferrara 2009; Salvadori et al. 2015). More luminous dwarf galaxies, instead, result from the merging of these small systems and more massive progenitors, which assembled at later epochs from metal enriched regions of the Milky Way environment, and have higher star-formation efficiencies. Their MDFs are hence peaked and shifted towards higher $[\text{Fe}/\text{H}]$, where CEMP-no stars can be more likely found.

Consequently, the fraction of stars at $[\text{Fe}/\text{H}] < -3$ with respect to the total dramatically decreases as the galaxy luminosity increases (Fig. 3). In Sculptor-like dwarf galaxies we find that these extremely metal-poor stars only represent $< 3\%$ of the total. Thus, we predict that CEMP-no stars at $[\text{Fe}/\text{H}] < -3$ are not lacking in Sculptor but they are *hidden* and thus more difficult to catch. We can then ask: how much should we enlarge the current stellar sample to uncover the low-Fe tail of the Sculptor MDF?

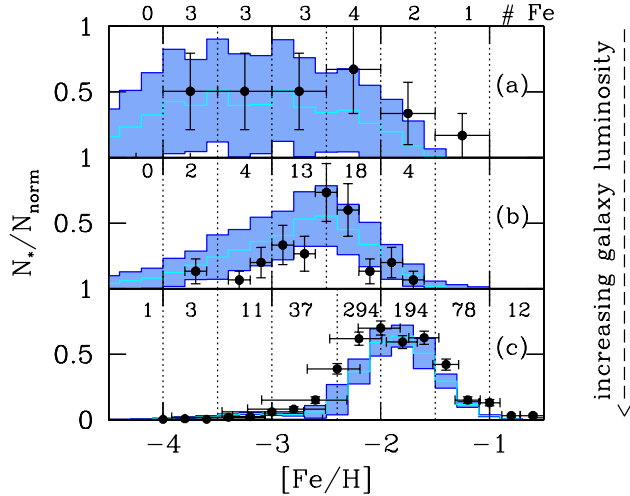


Fig. 3: Observed (points) and predicted (histograms) MDFs of: (a) ultra-faint dwarf galaxies with $L < 10^4 L_\odot$; (b) Bootes-, $L \approx 10^4 L_\odot$, and (c) Sculptor-like dwarf galaxies, $L \approx 10^6 L_\odot$. Labels indicate the number of measurements in each $[\text{Fe}/\text{H}]$ bin. We show the $\pm 1\sigma$ dispersion among 100 Monte Carlo sampling of the average MDF to the number of stars observed (see Salvadori et al. 2015).

4 Looking ahead: model predictions

Fig. 4 shows how many stars at $[\text{Fe}/\text{H}] < -3$ will appear in Sculptor by targeting fainter stars and thus increasing the overall sample of $[\text{Fe}/\text{H}]$ measurements. By using current facilities, we can follow-up stars down to $V \leq 20$. This might allow us to observe 12 ± 8 stars with $[\text{Fe}/\text{H}] < -4$, the $\approx 40\%$ of which should be CEMP-no stars. With new generation instruments and telescopes, such as MOSAIC on the ESO-Extremely Large Telescope, we will be able to dramatically increase the statistics by observing all the stars in Sculptor down to the main sequence turn-off (Evans et al. 2015). In this case, we might be able to catch ≈ 80 stars at $[\text{Fe}/\text{H}] < -4$ and ≈ 16 at $[\text{Fe}/\text{H}] < -4.7$, where the incidence of CEMP-no stars should be 100% (Fig. 4c, see Salvadori et al. 2015 for details). These experiments, therefore, will allow us to test the predominant role of faint primordial SN on early metal enrichment, along with the underlying hierarchical models for structure formation.

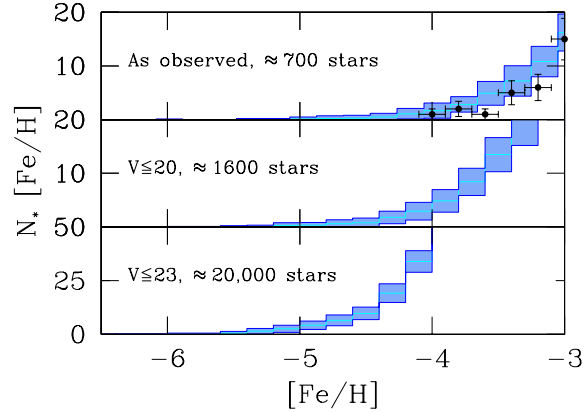


Fig. 4: Number of stars at $[\text{Fe}/\text{H}] < -3$ that are predicted to be observed in Sculptor by increasing the $[\text{Fe}/\text{H}]$ measurements. From top to bottom we show results for: i) the current statistics ii) stars with $V \leq 20$, and iii) $V \leq 23$. Shaded area show the $\pm 1\sigma$ errors (see Fig. 3).

In conclusion, Near-Field cosmology is a powerful strategy to (indirectly) study the properties of extinguished first stars and the physics of early galaxy formation. Larger stellar samples are required to tightly constrain the mass spectrum of the very first stars. In the nearby future, we will have at our disposal results from wide and deep spectroscopic surveys, such as those discussed in this volume. By combining theoretical and observational efforts we can exploit these data to unveil the first star properties. Thus, we are entering in the Golden-Era of Near-Field cosmology.

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References

- Aoki W. et al 2014, *Science*, 345, 912
- de Bennassuti M. et al. 2014, *MNRAS*, 445, 3039
- Bovill M. S., Ricotti M., 2009, *ApJ*, 693, 1859
- Brown T. M. et al., 2014, *ApJ*, 796, 91
- Cayrel R. et al., 2004, *A&A*, 416, 1117
- Evans R. et al., 2015, *A&A*, 416, 1117
- Helmi a. 2008, *A&ARv*, 15, 145
- Heger a., Woosley s. e., 2002, *ApJ*, 567, 532
- Hirano S. et al. 2014, *ApJ*, 781, 60
- Iwamoto N. et al. 2005, *Science*, 309, 451
- Karlsson, T. and Johnson, J. L. and Bromm, V., 2008, 679, 6
- Meynet G., Ekström S., Maeder A., 2006, *A&A*, 447, 623
- Norris J. E. et al. 2010, *ApJL*, 722, L104
- Placco V. M. et al. 2014, *ApJ*, 797, 21
- Salvadori S., Schneider R., Ferrara A., 2007, *MNRAS*, 381, 647
- Salvadori S., Ferrara A., 2009, *MNRAS*, 395, L6
- Salvadori S., Dayal P., Ferrara A., 2010, *MNRAS*, 407, L1
- Salvadori S. et al. 2014, *MNRAS*, 437, L26
- Salvadori S., Skúladóttir Á., Tolstoy E., 2015, *MNRAS*, 454, 1320
- Skúladóttir Á. et al. 2015, *A&A*, 574, A129